Renewable and Sustainable Energy Reviews 18 (2013) 401–415

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Mirrors in the sky: Status, sustainability, and some supporting materials experiments

Noam Lior*

University of Pennsylvania, Phialdelphia, United States

ARTICLE INFO

Article history:
Received 6 May 2012
Received in revised form
21 August 2012
Accepted 5 September 2012
Available online 20 November 2012

Keywords:
Space mirrors
Space energy
Solar mirrors
Mirrors
Cryogenic mirrors
Illumination

ABSTRACT

This paper critically reviews the state of the art of an approach to supply energy to earth from space mirrors that would be placed in orbit with angle control to reflect solar radiation to specific sites on earth for illumination, and also presents our (i) optical and mechanical tests to examine the property changes at a cryogenic temperature of thin film mirror that we manufactured, (ii) economic analysis related to several applications, and (iii) leading issues that must be taken into account in the sustainability analysis of the concept. The space mirrors were proposed to be of the order of a square kilometer or more each, planned to be made of thin plastic reflective films, which are launched to some optimal orbit around the Earth. One could, for example, thereby provide night or emergency illumination to cities and other locations, or illuminate agricultural production areas to lengthen the growing season, or to illuminate photovoltaic or thermal collectors on earth for producing electricity or heat. Proposals were also made for using such mirrors for weather modification, and we added here the possibility of using the space mirrors for shading the earth to reduce global warming. Experiments with space mirrors were conducted in the past by the former Soviet Union. Without (yet) consideration of environmental and social impact externalities, our economic analysis agrees with past studies that if transportation costs to mirror orbit are reduced to a few hundred \$/kg, as planned, the use of orbiting space mirrors for providing energy to earth is an investment with a good rate of return and a cost effective alternative to other power sources. This energy concept is very appealing relative to other options for addressing the severe energy and global warming problems that we face, and deserves much and urgent R&D attention.

© 2012 Elsevier Ltd. All rights reserved.

Contents

* Tel.: +1 215 898 4803; fax: +1 215 573 6334.
E-mail address: lior@seas.upenn.edu

1364-0321/\$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.09.008

1. Objectives and general background

This paper critically reviews the status and potential of space-based solar mirrors that reflect solar energy (light) for use on earth, as well as our experiments with manufacturing and testing a prototype thin-film mirror intended for that purpose.

Escalating problems of energy, environment and increased and more demanding population make it increasingly difficult to generate power, heat, light and food on earth [1,2]. As described in the publications by Glaser and co-workers (e.g., [3,4]), Mankins [5,6], Criswel and co-workers [7], Brown [8], Woodcock [9], NASA [10], Lior and co-workers [11–13] and many others, space has many desirable attributes for serving as the location for supplying energy to earth by constructing space satellite (SPS—solar power satellite) or moon-based power generation stations where the power is beamed to earth by microwave or laser for use. This topic has received significant support by the U.S. NASA during the late 1970s till the early 1990s, and beginning somewhat later but to some extent still continuing by several European countries and Japan. A web site of the National Space Society [14] keeps at this time a record of developments, an important recent update report "Space Solar Power: The First International Assessment of Space Solar Power: Opportunities, Issues and Potential Pathways Forward" edited by Mankins and Kaya having been published in 2011 [6].

Another space energy approach, which is the subject of this paper, is the construction and deployment of space mirrors that would be placed in orbit with orbit, angle and altitude control to reflect solar radiation to specific sites on earth for illumination (Fig. 1). These mirrors would be very large, typically of the order of a square kilometer or more each, highly reflective, planned to be made of thin plastic reflective films to minimize weight and cost, mounted in an appropriate light frame. They would be launched to one or more orbits around the earth. One could, for example, thereby provide night illumination to cities and other locations and for emergency lighting, or provide sunshine for agricultural production in some areas to enable or lengthen the growing season, or for applications such as crop drying ad water desalination, or to illuminate photovoltaic (PV) and thermal collectors (including salt-gradient solar ponds) on earth for producing electricity or for heating. This approach was originally briefly proposed by the space science pioneer Oberth in 1928 [16] who postulated a space-manufactured 5 μm thick mirror using sodium for the reflective layer, orbiting Earth in a 1000 × 5000 km orbit normal to the ecliptic plane. He estimated that a mirror weight of 10 t/km^2 (10 g/m^2) might be achieved, and also proposed to change its altitude by using it as a solar sail, all very close to NASA and other estimates and suggestions made about 60 years later. He believed that cost savings might be achieved if the construction material would be delivered from the moon or from an asteroid by means of an electric spacecraft. He suggested that the mirrors can be effectively used for warming and cultivation of Arctic land masses, for keeping shipping lanes ice-free, "some" influencing of the weather (incl. night frost prevention and precipitation control), night illumination of large cities and possibly the supply of solar power plants with additional light.

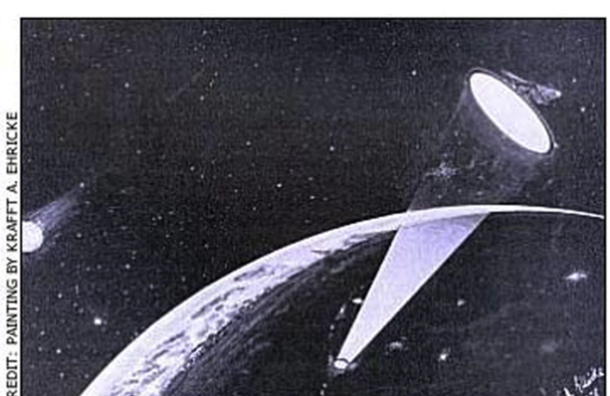

Fig. 1. Concept configuration of a space mirror reflecting solar light to earth [15].

This concept seems to have lain dormant and was then advanced most notably by Buckingham and Watson (in 1968, 60 years later [17]), NASA (Billman, Gilbreath and Bowen) [18–21], Ehricke [15,22,23], and others [24–26]. The review portion in this paper relies strongly on [17–23] in recognition of the pioneering work of these authors.

When considering space power generation, the major advantages of the space mirrors approach are: (1) instead of PV collectors on the energy source spacecraft there are only mirrors (optical reflectors), planned to be made from very thin film coated polymers (microns thick); (2) the energy is transmitted directly to earth in the form of solar light, without need for conversion of the collected solar energy to microwave or laser beams and their transmission through the atmosphere to earth; (3) sunlight is less threatening environmentally than the transmission of microwave or laser radiation; (4) no requirement for power management and distribution or thermal management systems on the spacecraft; (5) constructed of light thin (μm order) films, mirrors are easier to bring to orbit and deploy than the equivalent PV cells; (6) if used for power generation, it would probably need smaller collector and energy conversion fields on earth because of the safety-dictated need to make microwave beams diffuse when PV satellites are used; (7) no need for technical energy conversion systems on earth when the reflected sunlight is used for lighting, agriculture or bio-enrichment. There are, however, also a number of significant technical challenges: (1) the reflected sunlight arriving at the earth surface is more subject to the effects of weather, such as overcast, haze and atmospheric refraction, than microwave or laser beams; (2) amounts of sunshine reflected to earth that are sufficient to help supply significant fractions of needed global energy, and to be commercially viable, would require very large (order of 1 km^2 or more) mirrors, that must be optically flat (to a fraction of a wavelength of light) over these huge areas, and durable both mechanically and optically; (3) environmental effects, such as associated glitter and other "light pollution". These challenges have contributed to the fact that significantly less has been done so far, or planned to be done, on space mirrors, when compared with PV solar satellites.

A significant albeit brief step in the development of space mirrors was the Russian Space Mirror Project "Znamya" (banner) developed by the "Space Regatta Consortium" (SRC) [25] established in 1990 by the Russian space agency and the corporation Energia [27] (which specializes in space and launch vehicles and rocket boosters). The purpose of SRC in project Znamya, according to their official website, was the development of thin sheet technologies for solar reflection and solar sails and then for illuminating high latitude earth regions during winter months.

Detailed information about the Znamya experiments (Fig. 2) is somewhat sparse [24,25,27–29], and the following is available. The first SRC to be tested in space was "Znamya-2", on February 4, 1993. The mirror was a 20 m diameter circular 5 μm-thick aluminized PETF (Mylar) film, with an estimated areal density of 22 g/cm^2 that was composed of 8 sections with radial gaps between them. It was installed together with the unfolding mechanism inside the docking compartment of the cargo space vehicle Progress M-15 which disengaged from the MIR space station. Crew on board MIR were able to view and record the

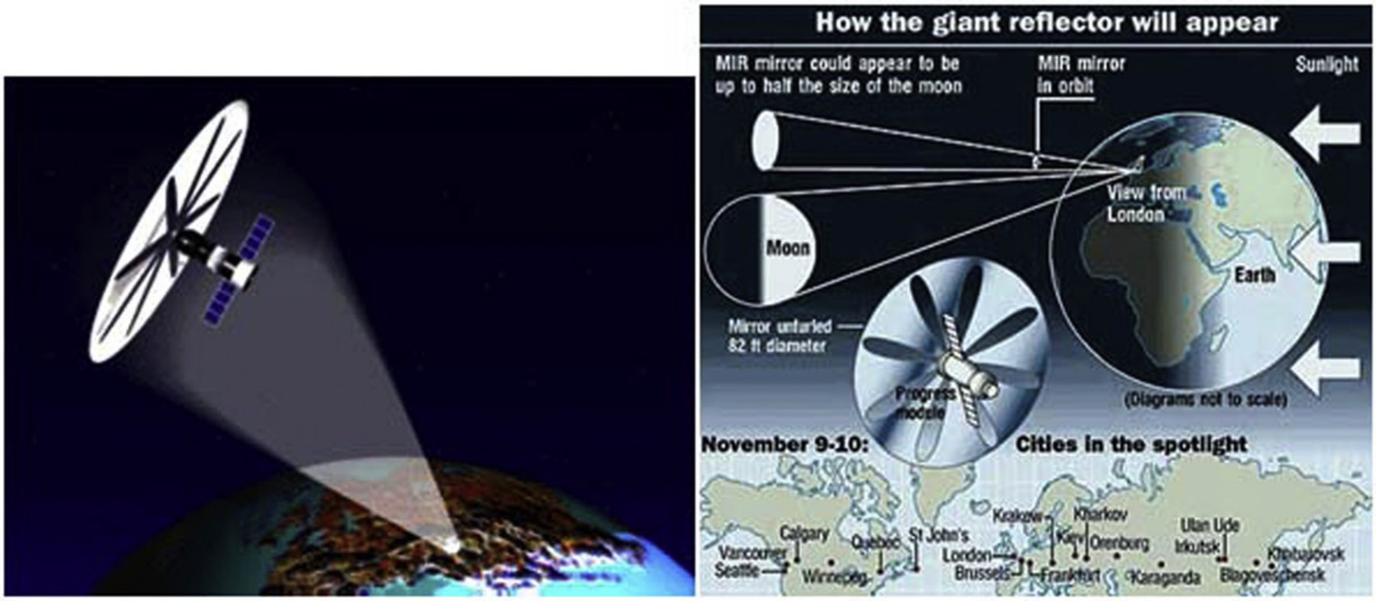

Fig. 2. Artists' illustrations of the Znamya solar reflector (a) [25], (b) [28].

Znamya 2 deployment, and the Progress resupply vehicle provided all necessary attitude control and manoeuvring. The unfolding mechanism had a spinning part with eight reels, one for each section of the reflective sheet. The sheet itself unfolded under the influence of centrifugal forces alone, as the unfolding mechanism was spinning. Once unfolded it was held taught by the spinning motion of the unfolding mechanism, which had a constant angular velocity of 1.8 rad/s after steady state was achieved, and did not use a skeleton support structure. The deployment test was successful. According to the SRC website, the spot of light produced by the mirror was about 5 km in diameter and moved across the earth's surface (starting in France and through Eastern Europe and Asia) at a speed of around 8 km/s. The brightness of the mirror as seen from the earth was reported to have been similar to that of a single full moon (<1 lx). The experiment was a success in two respects: it proved the feasibility of illuminating the dark side of the earth using reflective sheets (for example for use on cities that experience polar winters, and on disaster areas where light is needed) and as practice for handling thin sheets in space, the kind that could be used on spacecraft propelled by solar sails.

"Znamya 2.5" was the second attempt to launch a space mirror, as a continuation of SRC's space reflector experiments that was intended to lead to the deployment of 200-m-diameter reflectors. The reflector was 25-m-diameter and was constructed of materials and design similar to Znamya 2. The main goals of the Znamya 2.5 experiment were to verify the principal improvements of the film structure, to run the "Novey Svet" (new light) illumination experiment, and to operate the new manual attitude control mode to further test operational stability of the system and the film structure. Deployment of Znamya 2.5 was attempted on February 4, 1999. Unfortunately, due to a mission operations and software error, no command was sent to the Progress spacecraft to retract the Progress docking antenna. As the sail unfurled it collided with and wrapped around the docking antenna, entangling the sail petals around the antenna and each other. The antenna was retracted and an attempt was made to redeploy the reflector, however the reflector had been damaged by the antenna, and the whole apparatus crashed into the ocean. Since then, there have been no reported attempts to launch a solar mirror.

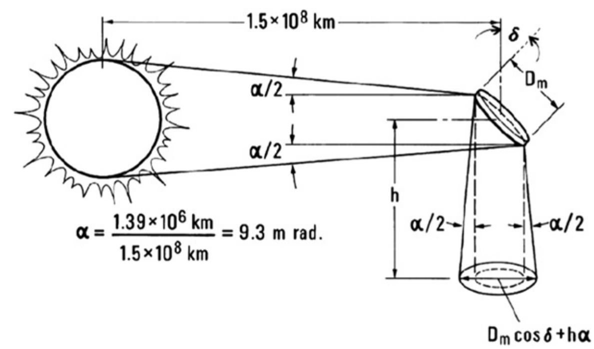

Fig. 3. The illuminated ground area as a function of the space mirror orbit altitude h. α is the angular subtense of the sun, D_m the mirror diameter, and δ the angle of incidence between the reflected beam and the illuminated earth spot [18].

The Znamya experiments received much attention from the media, including criticisms about light pollution that such space mirrors may create [30–36].

It appears that NASA has dedicated very small resources to research and development of space-based solar mirrors. It did perform some fundamental studies describe in Section 3 below and performed some slightly related experiments described here. In 1998, it launched an experimental satellite called Deep Space 1 that tested 12 different technologies in space, one of which was a solar concentrator array [37]. Although the array was used to focus sunlight onto photovoltaic cells and was not reflected to earth, it seems to have been the first experiment with concentrator arrays for power generation in space. In collaboration with industry and the Air Force, it also tested an inflatable solar concentrator array. The array was comprised of balloon-like concentrators made of thin polyimide substrate with metallic thin film coating that is already being used in space, which was reported to have performed within 10% of predictions and held its shape to within 0.8 mm. When inflated, it takes on a dish-like shape, which is comprised of a transparent front canopy and an aluminum-coated rear reflector. The inflatable design was many times lighter than rigid concentrator systems and occupies a very small volume before inflation, which reduces the cost of

transportation significantly. Furthermore, the fact that the reflectors are inflatable eliminates the need for complex mechanical actuators and human assembly, which also help to reduce the cost and increase safety—by reducing the probability of accidents occurring during assembly in space [38].

In the rest of the paper we show the basic equations for solar light reflection to earth, the different space mirror system concepts proposed, reflector configurations, energy considerations, our work on mirror materials and coatings, system economics and system sustainability considerations.

2. A few key equations for space mirrors [17–21,23]

The basic reflection optics are shown in Fig. 3.

For mirrors of diameters considered in the studies so far, the illumination I_e at the earth's surface by a space reflector in terms of solar illuminance I_s. reflectance ρ, cloudiness factor C ($C=1$ for cloudless sky), reflecting area A_r (of single or cluster of reflectors), angle of incidence δ between the reflected beam and the illuminated earth spot, and angle θ at the reflector between the incident and reflected light beam, is given by

$$\frac{I_e}{I_s} = \rho C \frac{A_r}{A_e} f(\varepsilon) \cos\delta \cos\frac{\theta}{2} \tag{1}$$

where $f(\varepsilon)$ is a function representing the intensity extinction due to haze and zenith distance (that increases the beam's path length through the atmosphere) and ε is the elevation angle of the reflector above the horizon; for $\varepsilon=0^\circ$, $f(\varepsilon)=1$.

Eq. (1) shows that he earth spot illumination intensity (I_e) increases in proportion to the reflector area (A_r).

If the solar reflector is above the atmosphere, as typically planned for such space mirrors, the solar radiation intensity at the reflector is at the atmosphere's edge, I_{sc}, the luminous solar constant is 133,334 lx or 134,108 lx and the solar constant$=1.3661$ kW/m^2.

If it is within the atmosphere, the illuminance I_s at the reflector is diminished by effects of air molecules, dust and water vapor along the beam path, with this diminution expressed by C_o, the overall coefficient of absorption ad reflection in a cloudless atmosphere, so

$$\frac{I_s}{I_{sc}} = C_o \tag{2}$$

The image area on the earth of an orbiting mirror of area A_r positioned at a height h above that image is expressed by

$$A_e = A_r + \tfrac{\pi}{4}(\alpha h)^2 \text{for a non-focusing reflector, and}$$

$$A_e = \frac{\pi}{4}(\alpha h)^2 \text{for a focusing reflector or point sources} \tag{3}$$

where α is the angular subtense of the Sun, $\alpha=1.39\times10^6$ km/ 1.5×10^8 km$=9.27$ mrad, $h=r-r_{\text{earth}}$, r is the radial distance between the orbiting mirror and the center of the earth, and r_{earth} is the earth radius. The area illuminated on the ground is an ellipse with major axis ($D_m+\alpha h\cos\delta$) and minor axis ($D_m+\alpha h$).

Eq. (3) shows that the illuminated earth area becomes gradually independent of the reflector area as the orbit altitude increases.

Very significantly, the overall reflectance of the mirror depends not only the surface specular reflectance but also on its flatness to within a small fraction of the sun's angular diameter α. This means (using Eq. (3)) that for maintaining the solar incidence intensity on the earth spot within 5% of the maximal, all parts of the mirror's surface must point in the same direction to within up to 2 mrad.

The reflector diameter influences the sharpness of the image. For a reflector of diameter D_r, the earth spot image will have a penumbra region of shadow of the same diameter, which thus does not practically affect the spot size.

For a synchronous orbit of $h=22{,}400$ miles (36,049 km), the diameter of the illuminated spot on earth is 208 miles ($\sim$335 km). Obviously, if a smaller illumination area is needed the satellite can be placed in lower orbits but then, as shown by Eq. (4), the illumination will take place for shorter periods of time. This can be remedied by using a number of mirrors in the same or similar orbits.

The period of a satellite (T) and the mean distance from the earth (h) are related by the equation:

$$T = \frac{2\pi}{3600}\left(\frac{h^3}{K}\right)^{1/2} \tag{4}$$

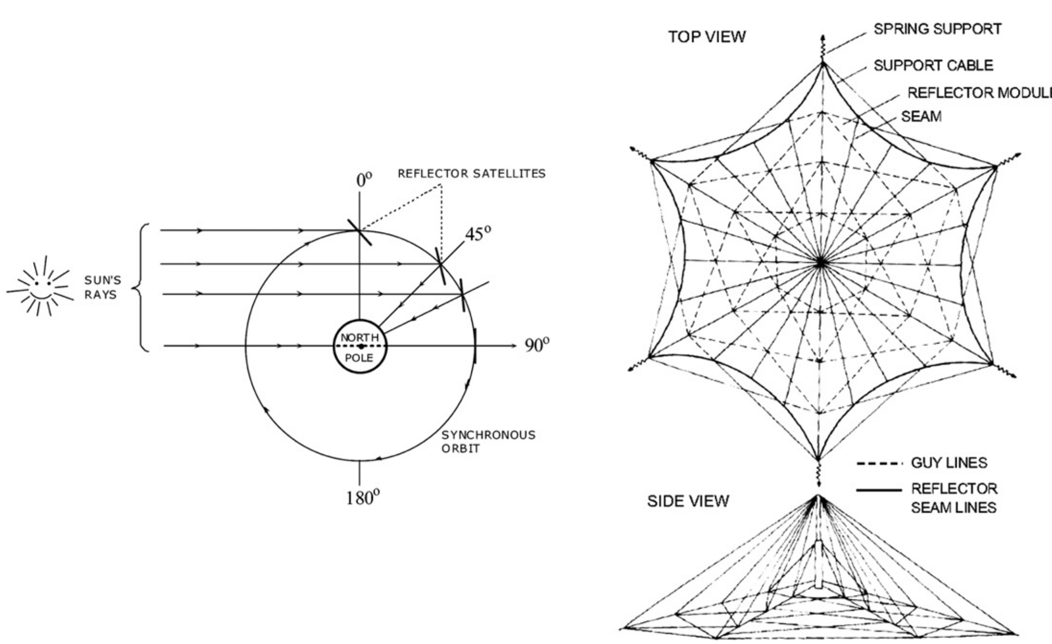

Fig. 4. Buckingham and Watson's basic concept of a reflector satellite and structure for supporting the thin-film mirror [17].

Table 1
Comparison of Ehricke's space mirror application proposals [22,23]. The proposed orbit periods are typically 2.5–3.3 h.

	Lunetta	Agrisoletta	Powersoletta	Biosoletta
Purpose	Nighttime illumination of Earth • Urban lighting • Remote industrial activities • Enables nighttime agricultural work	Agricultural enhancements • Weather stabilization • Precipitation management • Crop drying • Desalination	Daytime enhancement of sunlight • Power generation • Climate management	Daytime enhancement of sunlight • Agricultural enhancement
Total reflector area, km^2	15–30	2500–7500	10,000–14,000	100,000
Design	Cluster of 0.02–0.1 km^2 reflectors	Cluster of 5–10 km^2 reflectors	Cluster of 5–12 km^2 reflectors	Cluster of 70–100 km^2 reflectors
Illuminance of earth, solar constants	10^{-5}–10^{-3} (up to-1000 lx, 10–150 equivalents of the full Moon in a clear night)	0.2–0.6	1	0.3–0.6
Orbit	Geosynchronous	Sun-synchronous	Sun-synchronous	Geosynchronous

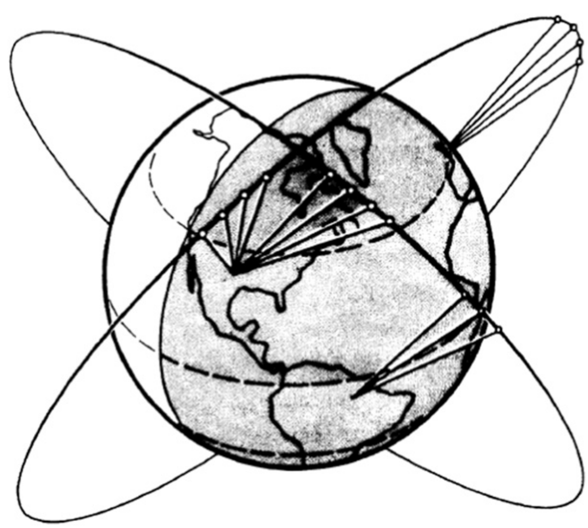

Fig. 5. The NASA SOLARES multiple orbiting mirror concept. Note 2 co-orbits and that several mirrors exposed to the sun at the same time are reflecting to the same earth spot [20].

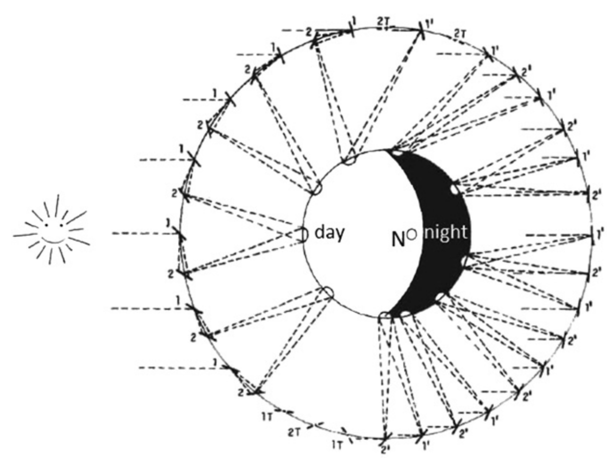

Fig. 6. Retro-reflection technique for daytime use of space light [23].

where $K \equiv GM_{\mathrm{earth}}$, G is the universal gravitational constant, $G = 6.673 \times 10^{-11}$ N m^2/kg^2, and $M_{\mathrm{earth}} = 5.9742 \times 10^{24}$ kg, so $K = 398{,}659$ km^2/s^2.

3. Space mirror concepts and proposed applications

Buckingham and Watson have in 1968 published a paper in which they described a system, shown in Fig. 4, in which a synchronous altitude satellite with a large reflecting surface is used to reflect the sun's rays to earth [17]. The reflector is required to continuously change its angle of incidence with respect to the sun-line to illuminate continuously a given spot on the earth.

They provided equations to calculate the illuminated area and illuminance with effects of cloud cover, and proposed structural methods for frames to construct such thin film mirrors, as that shown in Fig. 4.

They concluded that reflector satellites are technically feasible but quite expensive for illumination levels of 0.1 lx and higher, but may be economical for low levels of illumination of the order of 10^{-3} lx to 10^{-2} lx (less than 1/10 of brilliant moon light), useful for low-light-level sensors and could thus roughly double their utility for night use.

A very comprehensive conceptual, technical and socio economic study and exposition of space mirrors as conducted by the space visionary Krafft Ehricke [15,22,23]. He proposed and analyzed in some detail a number of generic applications for providing lunar-type night illumination service ("Lunetta"). solar type light energy services ("Soletta"), insolation for bio-production enhancement ("Biosoletta") to produce food and biomass, insolation for agricultural weather stabilization, precipitation management, crop drying and desalination ("Agrisoletta"), and insolation for generating electricity on earth ("Powersoletta"). Their main features are summarized in Table 1.

Ehricke made an economic feasibility study and predicted that very competitive electricity generation costs can be obtained; for example he predicted that Powersoletta with a PV energy conversion on earth can produce electricity at 4.8 c/kWh.

He added a number of new concepts [23] beyond past considerations:

- ○ use of a variety of sub-geosynchronous orbits, particularly, sun-synchronous ones,
- ○ "splitting" of large single reflectors into a number of smaller reflectors operating in cluster to reduce the size of the individual reflector, lower cost, and increase system robustness. The illumination pattern in this configuration is determined by the number of co-orbits, the time position of their maximum latitude passage, and the lighting power (number of reflector units) assigned to each co-orbit.

- splitting of one orbit into several co-orbits (Fig. 5) which is particularly advantageous for urban night illumination where multi-directional illumination creates a more diffuse and uniform lighting effect;
- More possible applications;
- the concept of retro-reflection (called by some others “relay mirrors”), i.e., reflecting light from a mirror that does not have direct optical sight line to an area on earth that needs to be illuminated, to one in orbit that does (Fig. 6; thus enabling day and night operation raises the system’s utilization factor.

We add the possibility of using the space mirrors for shading the earth, an application that may be locally useful for a number of obvious reasons, or as a geo-engineering way to reduce global warming, a concern that did not exist when the early researchers did their studies of solar mirrors in the 1970s. In the extreme case, the mirrors, or some of them, could be turned towards the sun and thus prevent the solar radiation reaching the atmosphere and earth area that are that is then in the mirrors’ shadow.

NASA performed some detailed preliminary feasibility studies of the design, deployment and use of space mirrors, published in the late 1970s [18–21], and concluded that “The use of orbiting mirrors for providing energy to ground conversion stations to produce electrical power is shown to be a viable, cost effective and environmentally sound alternative to satellite solar power stations and conventional power sources.”

Their proposal, which they called SOLARES, was to use a cluster of free-flying very lightweight (10 g/m^2) metal-coated polymeric film mirrors, optimally 1 km^2 each which, after deployment at altitude of 800 km, are placed in operational orbit and controlled by solar radiation pressure, to almost continuously illuminate a chosen surface on earth an intensity of I_e–1 kW/m^2 (“at a fairly constant level”, which, however, must take into account atmospheric variability with time). This would increase the available insolation at the earth energy collection and conversion station about 4-fold, and, if the insolation is uniform enough over time would also eliminate or reduce the need for energy storage.

They developed equations showing the influence of a number of parameters – mirror altitude, orbit inclination, period, mirror size and number, and atmospheric effects – on the reflected insolation that may be received by a round spot as a function of location. In their economic analysis they found that generated electricity costs range may be as low as about 1.6 c/kWh (in 1977/8 US cents), and we note that this was based on PV system costs {\$5/kW$_{peak}$) that have since then dropped. They found that the ground station for converting the solar radiation received from the mirrors to electricity by using PV is the major component of the total system investment, since the cost of reflectors in space is much lower. At the same time, as discussed in more detail in Section 7 below, they used extremely low costs for transportation into orbit, which make the costs of electricity and heat generated they determined much too low when considering current technology. As the environmental issues of principal concern they identified the perpetual twilight that neighboring communities might experience and the land area required, and felt that atmospheric effects are minimal and to their opinion perhaps beneficial. More details about their economic and environmental study can be found in Sections 7 and 8. They expressed the opinion that SOLARES could supply the entire global energy requirement.

Other authors have proposed mirror deployment at geostationary orbits (GEO), but as Eq. (3) shows, at this altitude of h=35,800 km the area illuminated on earth would have the huge diameter of about 3329 km. At the chosen ground intensity of 1 kW/m^2 the mirror area would then have to be about 150,000 km^2. The annual energy generated at one such location with 15% ground conversion efficiency would be, if atmospheric solar radiation transmission effects are ignored, up to about 41,200 EJ, 82 fold of the current world usage of 500 EJ. To achieve a practical ground area size with realistic capital investment and energy output, to provide energy to more than a single ground station, and to be able to employ the enhanced insolation for nonelectrical applications if desired, they postulated the use of a large number of flat 1-km diameter reflectors in lower orbits (Fig. 5). Such configuration would allow each selected ground site could be insolated at all times (excluding eclipse and inclement periods), and any given mirror could be used for other tasks, including the insolation of other sites. The use of many and small reflectors clearly also allows the desirable feature capability of incremental implementation and easier repair and replacement.

Smaller reflector areas also require much lower torque for their control, since their moment of inertia scales as $I_i \sim \sigma A R_i^2$ t where σ is the average areal mass density, A is the mirror area and R_i is the characteristic radial dimension along the ith rotational axis.

These NASA studies also calculated the daily and annual variation in the solar flux, both the natural one and that supplied by the orbital mirror system, and it is shown in Fig. 7. The most impressive feature is that although the direct solar input varies seasonally by more than a factor of two, the mirror input is constant to about 10%, making the system suitable for baseload electricity generation use.

Thorough techno-economic analysis is required to find the optimal system, so they only considered an example of the mirrors at an altitude of 4146 km in a 3-h periodic orbit. The mirrors would be deployed or erected at an altitude of approximately 800 km. From this altitude, where the solar radiation pressure is much larger than the drag force, it is possible to “solar sail” the mirrors to their operational orbit (i.e., 4146 km), requiring about a 3-mo transit time.

Using Eqs. (1) and (3), and as best it can be concluded from [18–21] assuming 23% losses and geometric spreading due to the sun-mirror-site angle, eclipsing, non-zenith mean apparent reflector location and atmospheric effects, 62,800 km^2 of mirror area was stated to be required to deliver an average 1.25 kW/m^2 (0.25 kW/m^2 from regular solar incidence +1 kW/m^2 from the mirrors) to ground stations at 30° latitude. With their proposal to build individual mirrors of 1 km diameter each, this translates to the need for 80,000 orbiting mirrors having a total mass of about 6.3×10^8 kg. This mirror system was estimated to be able to supply this flux to at least 5 (of a theoretical 13) ground sites around the world. For each

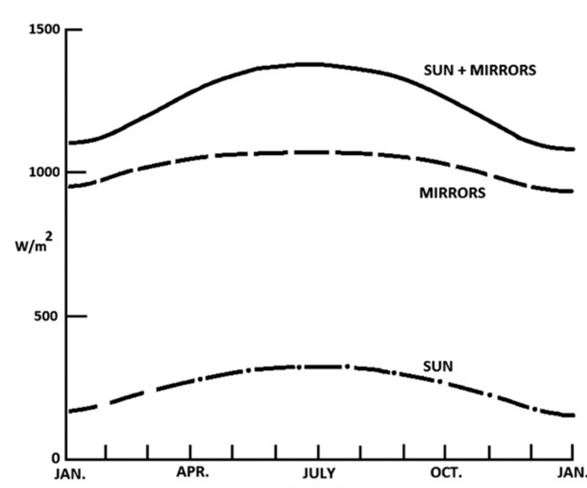

Fig. 7. The annual variation of the solar flux at the area illuminated on earth by the sun alone, by the proposed mirror system, and by their combination [21].

site, about 70% of the incident insolation falls within area of diameter $h\alpha$ (38.4 km, A_e=1167 km^2) and 99% within 2 $h\alpha$ (76.8 km, A_e=2334 km^2). We note that a conclusion from [19] appears to be that the ratio of the mirror area and the ground area steadily insolated with the added 1 kW/m^2 from the mirrors is 62,800/(5 × 1167)=10.76. With 15% conversion of just the $h\alpha$ insolation to the five ground stations, up to 27.6 EJ of electricity can be generated, amounting to about the electricity generated globally in 1977 (at the time of the NASA studies) and 36% of the electricity generated in 2010. Power generation would of course increase with the PV conversion efficiency, which indeed shows continuous improvement. After deducting the energy converted in the PV system, the remaining 85% of the energy at $h\alpha$, as well as the energy in the annulus between $h\alpha$ and 2 $h\alpha$ could additionally constitute a large usable energy resource.

4. Some reflector configurations

The reflector may be of any geometry, usually dictated by structural and weight considerations, and the mirrored surface may be flat, as proposed in most of the studies, or curved for concentration. If the reflector is so large that its size may no longer be regarded as a negligible fraction of its image size a curved concentrating surface is needed. It is noteworthy that it may be possible to vary the concentration (curvature) as needed during the orbital motion of the reflector.

Concentration onto a terrestrial site can also be obtained by orienting the beams from several orbital mirrors to the same spot, as shown in Fig. 5 and also discussed in [26]. This is essentially a Fresnel field reflector (in [26] called "compound mirrors"). This configuration also allows more uniform illumination: for example, when one of the compound mirrors is located in the Earth's shadow, the other mirrors may be illuminated and reflect to the receiving area. The angular displacement of the compound mirrors should thus not be less than 20° apart, since otherwise all three mirrors may be in the Earth's shadow at once.

Based on such a concept, the NASA [21] study proposed that the additional insolation from the space mirrors can be significantly greater than average ambient sunlight, and they have chosen to supply an earth surface solar intensity of $I_e \sim 1$ kW/m^2 for sizing the space system and ground stations and for deriving costs. They point out that the maximal average U.S. value of normal sunlight is about 0.25 kW/m^2, and therefore this increase intensity should reduce the area-related terrestrial solar converter system costs (for collectors, converters, land preparation, etc.) fivefold [(1+0.25)/0.25–5] from that of a solar power generation system of equal output that operates without the space mirrors.

The NASA study [18–21] has shown that for a given orbital inclination the number of mirrors needed to provide continuous insolation at a given ground site increases with decreasing altitude, and thus the total mirror area for a fixed ground site intensity decreases. However, several factors place a limit on the lowest usable altitude. First, atmospheric drag necessitates an altitude above 1500 km for the 15 g/m^2 structure they proposed to allow a system life of 30 years. A remedy is to employ solar sailing for countering drag, thus perhaps providing the desire system life down to altitudes of 1000 km. Second, the angular acceleration needed for the mirror to insolate a given spot during its transit varies approximately inversely with the third power of the altitude, thus creating significantly tougher demands on structural characteristics and control at lower altitudes. Third, lower orbits increase the fraction of time the mirror is eclipsed by the Earth. They thus concluded that the lower bound for an operational reflector system is probably not less than 1000 km.

5. The energies: Generation and embodied

As stated above, the reflected insolation to a ground area can be augmented by using the space mirrors as a Fresnel field. For various environmental and social reasons it is safer to limit the $I_{e,m}$ reflected from the mirrors to approximately maximal natural levels and in the NASA study [18–21] it was proposed to make it 1 kW/m^2. This would be suitable for agricultural as well as heating and power generation purposes. Atmospheric radiation-loss effects have been considered in the estimation of the required mirrors' area, and to avoid the important losses due to persistent cloudiness (scattered clouds were indicated to have minimal effect), it is recommended to install the mirror-illuminated ground stations in sunny regions that experience least cloudiness. It is important to keep in mind that the space mirrors eliminate the diurnal and seasonal periodicities due to the rotation of the earth and the sun. Based on global insolation data, it was assumed that the time-averaged insolation without the mirrors is 0.25 kW/m^2, for a total ground insolation of 1.25 kW/m^2.

On this assumption The NASA study found that the total energy used to produce the SOLARES space system (mining through turn-on) was about 1.5×10^{12} kWh. With the above assumption of I_e=1.25 W/m^2 and a 15% ground conversion efficiency, this embodied energy is equivalent to only 10 weeks of energy production at the five ground sites. Inclusion of the ground system added from 4 to 15 weeks to this number, depending on the conversion technique.

6. The space mirrors

6.1. Materials and optics

The design of the mirror needs to provide maximal specific power reflected with very low weight and payload volume. Its surface must have a reflectance (ρ) that is as close as possible to 1.0, it must be accurate enough to ensure that most of the solar radiation reflected from its surface arrives at the minimal earth site area dictated by the fully-planar mirror optic, it must be durable and easily deployed and the material needs to withstand years of solar winds, radiation, and the extreme temperatures and their variations in space. Importantly, the mirror is exposed to micro-meteorites, space debris, electromagnetic radiation from sunlight [39], including solar wind, comprised of streams of particles originating from the sun and propelled by the Earth's magnetic field. The composition of solar wind includes approximately 2×10^8 H^+/cm^2 s protons (96%), of about 6×10^6 alpha particles/cm^2 s (3–4%) and a few 10^5 ions/cm^2 s of higher mass with average velocities of about 400 km/h (corresponding to energies of 0.85, 3.4, and 10 keV, respectively) as well as 3–30 keV electrons. There are also some occasionally emitted particles as the result of solar flares or storms.

In the experiments of [39] a rapid worsening was found in the optical properties, including loss of reflectivity and defocusing due to blistering, due to the effects of solar wind, affecting the very beginning of a solar mirror's operation. They suggest that the mirror's film thickness should be at least 0.1 μm, which is the maximum penetration depth of the solar particles. As discussed below, this is also the same minimal thickness required for the metallic thin film to remain opaque to visible light and to other low frequencies of electromagnetic radiation. Another type of radiation is the ultraviolet (UV) part of sunlight with wavelengths between 4 and 400 nm. Two UV bands are particularly relevant to materials degradation, the near UV range (200–400 nm) and vacuum UV range (100–200 nm) [40]. This type of radiation causes the greatest material degradation to polymers, because

many of their bonds can absorb UV light, which in turn can cause photochemical reactions. These reactions can result in discoloration or loss of mechanical properties due to chemical changes in the material. Most of this damage is sustained by the first 0.3 μm from the surface, the UV attenuation depth. Therefore, if a polymer film's thickness is greater than the UV attenuation depth, the degradation sustained should have little effect on the bulk properties of the polymer.

The commonly used and proposed mirror is a thin film one, a few μm, made of a polymeric substrate coated by a thin reflective film. In addition to serving as the reflector, the metallic reflective film coincidentally also serves to at least partially protect the upper part of the polymer substrate from UV degradation. The weight, including the film framing was estimated to be under 10 g/m^2 of surface. The development of film mirrors is synergistic with many other applications, including the strong interest in several countries to develop solar sailing, using the solar radiation pressure, as a means for relatively inexpensive and energy-independent deep space transport. For example, Friedman et al. [41] predicted that polymeric sail-quality materials will be available (by 1985) with an areal density of 5 g/m^2.

A commonly used mirror substrate is polyethyleneglycolterepthalat (PETP) with the net composition $(C_{10}H_8O_4)_n$, known as Mylar, Hostaphan, etc., and are produced by companies like Bayer, and Du Pont, and Kapton, which is poly(4,4′-oxydiphenylene-pyromellitimide) made by DuPont. They are coated with a thin film metallic surface by chemical vapor deposition (CVD) to provide high reflection. The most common metal is aluminum due to its good reflectance and low cost, but gold and silver were also used for small mirrors due to their stability or higher reflectance. Other materials were also tried due to their higher reflectance and deterioration resistance under space conditions (e.g., [42–44]).

Various coatings over the reflecting film were also tried as they can provide increased wear resistance and better UV degradation resistance as well as increase the reflectance, for example some thin dielectric coatings were shown to increase the reflectivity of a metallic surface to over 99.8% at design wavelength [45]. The coating material for oxidation protection in this environment must be transparent to solar radiation in the wavelength region of interest, generally 200 to 2500 nm, must be easily applied, strongly adherent, have low toxicity, and be of low cost, and must be resistant to atomic oxygen. In a NASA study [46] materials proposed for such use included several metal oxides, such as aluminum oxide, silicon oxide, and indium–tin oxide as well as magnesium fluoride and silicon nitride. MgF_2, SiO_2, and indium-tin oxide exhibited least loss of reflectance when exposed to a space-like environment, in that order. It was also found that oxidation of the ref1ective layer and/or the substrate in areas adjacent to a pinhole defect, but not directly exposed by the pinhole, can occur. In these experiments the exposure was up to 634 h, so much longer exposures maybe by three orders of magnitude, are needed for proper evaluation for space mirror application that should have a life of several decades. In such a protected mirror, the mirror would thus have a sandwich configuration of at least 3 layers: bottom is the polymer substrate, middle is the metallic (say Al) reflecting film, and the top is a transparent protective layer.

It is generally agreed that the film mirrors should be maintained periodically, say once in 10 years, by applying a thin fresh Al (or other reflective material) layer in situ, which could be accomplished by flying a furnace with evaporating Al along the foil surface at a certain distance [39]. This was expected to restore the initial reflectivity (smoothing of the blistered flaked areas), and sintering together the eventual brittle foil surface areas (flakes) by the freshly evaporated material. to prolong the mirror reflectivity to the order of a 100 years. Such maintenance would also be needed to repair possible holes due to meteorite impact, or for replacement of part or all of the reflector film. It was estimated, however, that meteoroid damage would be very small, 3% for 30 years in orbit [18].

Decrease of the reflective coating thickness, desirable for cost and weight reduction, is limited by its becoming transparent (typ. below 0.1 μm) and their deterioration resistance due to ambient conditions. Furthermore, reflecting film transparent to high-frequency (X- and γ-ray) radiation [47] may cause damage substrates if they are susceptible to that.

Roughness of the reflecting film surface increases light scattering and thus reduces its reflectance, indicating the need for smoothness.

The solar mirror must have mechanical properties that can withstand its temperature in space, that goes down to about 3 K (with the associated embrittlement) but also rises to much higher values especially on its non-reflecting parts which are intermittently exposed to the sun. The mirrored surface substrate has the leading role in the mirror's overall structural integrity.

The mechanical stresses in the mirror are composed of those inherent to thin films, those imposed by the mirror frame that must keep it stretched to the desired shape (planar, or curved if concentration is desired), solar radiation pressure and wind, as well as those associated with angle and position manoeuvres. Even without stressing by external forces, stresses in thin films on thick substrates can be quite large, commonly hundreds of MPa, when compared to the same materials and configuration in bulk form. The stress is first developed during the thin film deposition, and then during the use of the solar mirror. During deposition of a thin film material onto a substrate, the thin film material is often far from its melting temperature and consequently the atoms are insufficiently mobile to attain minimum energy positions during the deposition, this leading to the formation of stresses between the thin film and the substrate. During mirror operation a second stress will occur due to differences in thermal expansion between the reflective film and its substrate. If the difference between the, respective, expansion coefficients is $\Delta\alpha_e$, and the temperature changes are ΔT, the resulting stress is proportional to $\Delta\alpha_e\Delta T$. Mechanical failure, such as cracking under tensile stress if the film is brittle, or delamination, may result from these stresses.

6.2. Our reflective thin film mirrors construction and experiments

We have investigated the fabrication of thin film mirrors akin to those that were considered suitable for space mirror application (Sections 1, 3, and 6.1), and then examined their microscopic surface quality and measured their reflectance, tensile strength, and creep (fatigue) at both room and cryogenic temperatures, i.e., 300 and 77 K, respectively.

Based on a list of the most common space materials used by NASA, the polymer substrate was chosen to be the polyimide Kapton HN (Dupont) because of its much greater tolerance – by as much as three orders of magnitude – to radiation, such as UV and soft X-Ray, in comparison with another commonly used polymer, Mylar (PETP) [47], and because of its proven performance in temperatures near 0 K and greater resistance to high temperatures, and its higher tensile strength [48]. Kapton is commonly used by NASA for thermal insulation on its space vehicles, satellites and telescopes [49].

Aluminum was chosen as the reflective thin film because it is a commonly used reflective material for thin film mirrors [48,49], primarily because its density is an order of magnitude and its cost is two orders of magnitude lower than silver, which is often used for mirrors. Another deficiency of silver films is their semi-transparency in the UV band, which allows a faster degradation of the organic substrate films.

Fig. 8. Our manufactured reflective thin film.

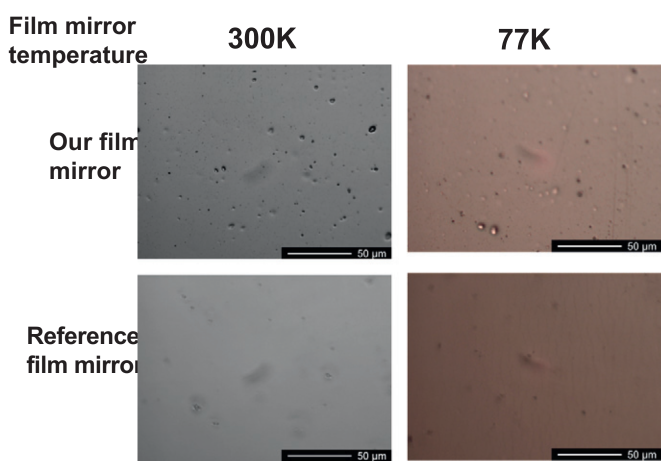

Fig. 9. 500X microscope surface photos of our thin film mirror and of the reference one, at 300 and 77 K. *Note*: the bean-shaped dark area in the center of each photograph is a smudge on the microscope lens, not a defect.

The thickness of the Kapton film substrate was chosen to be 7.6 μm, as thin as Dupont had commercially available, with that thickness often used by NASA but that could be reduced on special order. The thickness of the aluminum coating for deposition onto the Kapton film's surface was chosen to be 100 nm, again as done by NASA and following previous studies [50,51]. The size of the available vacuum evaporator dictated the diameter of the mirror film to be 134.6 mm.

The pure aluminum coating was done by vapor deposition which is preferable to sputtering, because sputtering tends to brings about low hardness, no true endurance limit, rough surface topography, and poor resistance to stress induced hillocking [51]. No other coating, such as commonly used protective ones, was added. To maintain the manufactured film mirror surface planar, at least on the macro-scale, a supporting structure in the form of two concentric rings was made from Delrin®. The manufactured film mirror supported by the ring structure is shown in Fig. 8.

The film reflectivity was measured as a function of wavelength in the visible light range (300–1000 nm), at ambient and cryogenic temperatures, by using a spectrophotometer, using as reflector reference a commercially available reflective mirror film (PMMA with Ag coating) made by 3 M [52].The cryogenic temperature was obtained by immersion in liquid nitrogen (~77 K) for 60 min, which is obviously higher than the minimal space temperature of about 3 K, but is much easier to attain experimentally.

Both our film and the one from 3 M had lower than average reflectances than commonly available due to handling and manufacturing problems, and also absolute values of the measured reflectance were subject to large experimental error. Importantly, however, the trends are consistent: the reflectance at 77 K is always higher than that at 300 K. For example, in the peak solar wavelength range of 470–700 nm the average reflectance at 77 K is about 1.42-fold higher than at 300 K for our sample and 7% higher for the 3 M film. The reflectance of our film is about 5% and 24% lower than that of the reference one at 77 and 300 K, respectively.

The film transmittance was measured too, in the same wavelength range and was found to be zero for all films tested, at both temperatures.

While surface contraction at the cryogenic temperature, resulting in contraction of pinhole and other defects may partially explain the increased reflectance, much more detailed examination of the films, including adhesion of the aluminum to the Kapton substrate, thickness and quality uniformity, and defect density, would need to be conducted for full understanding of the reasons for that reflectance–temperature relationship.

To better understand the results from the measurements, samples from the test, of both the mirror film we manufactured and the commercial 3 M reference sample, were examined by an optical microscope. The first set of these two samples were kept at ambient temperature (approximately 300 K), and the second set was exposed to at least 60 min in an isothermal container with liquid nitrogen (~77 K). Once the samples were removed from the nitrogen bath, they were rapidly cleaned and observed and photographed at a magnification of 500. The surface photographs are shown in Fig. 9.

Fig. 9 shows that the number of defects/imperfections per unit area (i.e., surface defect density) is higher for our film mirror than for the reference one. These defects include mostly pitting for the samples and spits in the standard, typical of using a vapor deposition. This may therefore be the reason for the measured lower reflectance of our mirror. Since the vapor deposition process we used can be improved significantly, there is no doubt that better reflectance can be obtained, as shown by many.

An interesting observation is that for both films the imperfection surface density is lower for the cryogenic temperature, perhaps thus justifying the higher reflectance at this temperature. Another interesting observation is that nevertheless, the reference

Table 2
Coefficients of thermal expansion for materials used in standard (Ag and Mylar) and sample (Al and Kapton), [53,54].

	Coefficient of thermal expansion (ppm/°C)
Silver (Ag)	19.7
PET (Mylar)	117
Aluminum (Al)	~23
Kapton (Polyimide)	20

Table 3
Measured mechanical properties for our film mirrors exposed to 300 and 77 K.

Film temperature, (K)	**Ultimate tensile strength (MPa)**	**Young's modulus (MPa)**
300	9.9	129
77	13.3	448

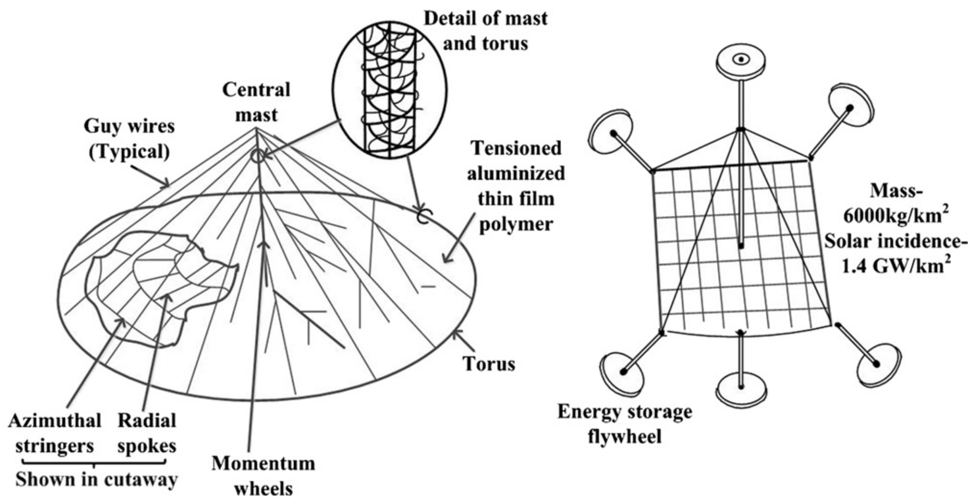

Fig. 10. Proposed structural configuration of a space mirror and its flywheel control system [18,21].

film experience significantly higher degradation when exposed to the low temperature, as shown by lines the along the vertical direction of the image that appear to be micro-cracks that formed after exposure to liquid nitrogen (~77 K). In fact, when the reference film was placed into the liquid nitrogen it made a loud crackling noise that lasted for a few seconds, while no sound was heard for our film. In contrast, the sample did not emit any sounds when placed inside the container. No micro-cracks developed in our film. The likely explanation is that the thermal expansion coefficients of silver and Mylar (the reference film) differ by 6-fold, while those between Aluminum and Kapton (our film) differ by only ~15%. To help explain why this phenomenon occurred, consider Table 2.

We note, however, that the developed micro-cracks in the reference film did not decrease its reflectance.

Table 3 shows the experimental values for ultimate tensile strength and Young's modulus from our mechanical tests.

While the absolute values measured here for the mechanical properties at the cryogenic temperature are subject to a large experimental error, the observed trend are consistent with the behavior of thermoset polymers, like polyamides, which are characterized by a high tensile strength and modulus with a small total elongation, prior to failure, brittle behavior, and an increase of the ultimate tensile strength and tensile modulus at lower temperatures. All of these characteristics were identified in the experimental load-displacement curve and in the results shown in Table 2. At 300 K our film was found to exhibit very low creep, 4.5% drop in load as a result of keeping a constant displacement. Experimental difficulties prevented the measurement of creep at 77 K.

6.3. Mirror mounting structures

The structure must of course support the reflective mirror film, but must also provide the necessary tension for maintain its shape, as well as the control mechanism for adjusting its orientation during flight as needed. The huge size of these mirrors mandates assembly in space, with the components ferried to the location by a cargo space vehicles, and then constructing the frame from its component and finally unfurling the reflective film and attaching it to the frame. As described in Section 3, the NASA plan was to do the assembly at an altitude of 800 km and the ferry the mirror into its final orbit by solar sailing.

For the SOLARES concept, NASA's study [18–21] has proposed mirror structures, shown in Fig. 10, which, although not yet optimized, "can work". The aluminized film was assumed to have an areal density of 4.0 g/m^2. The film is tensioned onto a supportive structure consisting of an outer torus with radial-segmented spokes and concentric rings. Such tensioning is necessary to maintain the reflector planarity within 2 mrad (as shown in Section 2, this is deemed as adequate to maintain a flatness that will not increase the spot size by more than 5% over that of a perfectly planar mirror) despite the perturbing radiation pressure, gravitational gradient, and angular acceleration forces acting on it. The rim torus must have sufficient buckling strength to provide this tension. The rings and spokes are stiffeners to reduce mirror sag and need be only a small mass fraction of the structure if sufficient tie-wires are provided to the mast to enhance the ring stiffness and transfer forces to the mast. This central mast and guy-wire system prevents out-of-plane buckling, despite the requisite torques that must be used for mirror pointing and control.

They proposed that the support structure would be fabricated from a high-modulus carbon-fiber–epoxy (or polyimide) matrix composite. In practice, the torus and mast would be open lattice work, crossed-braced assemblies, or woven structures, using eight-ply composites.

Their design postulates centrally located pairs of momentum flywheels to provide turning torques as needed for targeting radiation onto a ground site and for providing steering corrections between sites. The wheel pairs can change their relative speeds (mirror rotation rate) via a coupled motor–generator. Solar-cell-derived electricity is used initially to spin up the wheels and to make up frictional losses.

The design draws on interest in the constructing and using solar sailing for transporting payloads in deep space exploration, in one case of which an ultralight truss mast that can be deployed to kilometer lengths was designed, and a means to fabricate a large quadrant of sail material and stow it without material creasing or trapped air were proposed [29,41,55,56]. Sailcraft areal densities ranging from 8.9 g/m^2 down to 4.6 g/m^2 were proposed by NASA as a goal, and since the sail material used in NASA experiments had an areal density of 3 g/m^2, this leaves 1.6 g/m^2 for the supporting structure, bus and payload. This proposal was for a deployable mast design, sail fabrication and stowage, sail/mast deployment, and integration of the sailcraft in a launch vehicle, all of which were reported to satisfy the solar sailing requirements within this weight restriction.

Parallel applications of more immediate interest are high-precision (shape accuracy in the range of at most mm rms) space

reflectors for communications, earth observation, or radio-astronomy. The flexible reflecting surface can be of knitted mesh, tensed metalized membrane or parabolic quasi-membrane (flexible shell-membrane). At a few tens of meters in diameter, the ones considered are orders of magnitude smaller than space mirrors and they can afford an order of magnitude higher areal mass of typically 0.5 kg/m^2, (mostly using carbon-fiber composites) but some of the goals and technology are synergistic. Here we mention the work by Datashvilli, Baier and co-workers [57,58], with small models of their design shown folded and then deployed in Figs. 11 and 12.

Fig. 11. Deployment of membrane reflector model (0.6 m diameter), (a) stowed, (b) deploying, (c) (scaled) deployed [57].

7. System economics

While it is obviously extremely difficult to predict the costs of generated energy by space mirrors, because of the novelty of the concept, uncertainties about developments that will arise during the decades needed for its materialization, as well as about all of the externalities that will accompany it, several economics analyses were conducted to at least provide an initial prediction.

As an example of the order of the needed investment, a study by Ehricke in 1979 [23] estimated that the investment for Biosoletta (with 10,000 km^2 total mirror area, Table 1) is about \$1200 billion, that is about \$80 billion/year for the 15 years construction time he predicted.

The NASA economic analysis of their SOLARES space mirror concept [20] (see also Section 3) to supply approximately the entire electricity demand at that time (32 EJ, which in 2010 was 77 EJ [2]) based on a desired 15% capital return, 30-year system life, and a load factor which takes into account eclipse and inclement periods, found that generated electricity costs should range from about 2.5 c/kWh to less than 16 c/kWh (in 1977 US cents), and that the ground station for converting the solar radiation received from the mirrors to electricity by using PV is the major component of the total system investment, since the cost of reflectors in space is much lower. We note that this was based on PV system costs of \$5/W_{peak} that have since then dropped up to less than \$2/W_{peak} [59], but that is likely to have been the case for other components of the space mirror system. The same study states that if the solar radiation incident on earth from SOLARES was used just as heat, the cost would be about 1c/100 MJ thermal.

In that analysis, performed on the premise of making 80,000 space mirrors of 1 km diameter each to be placed in a 4146 km altitude orbit, they assumed the use of a thin film mirror made of a 0.1 μm Al reflector on 2.5 μm polymer substrate weighing 4 g/m^2 and the structure from HM graphite–epoxy. The total mirror weight, including also controls, instrumentation and growth allowance, was estimated to be 10.01 gr/m^2, i.e., 7860 kg/mirror, and the total cost of the mirror including prorated R&D costs excluding transportation costs into orbit was \$1,654,000 per mirror, i.e., \$2.11/m^2. Including the transportation they came up with a total price of \$2 million per mirror, i.e., \$2.55/m^2. They estimated the cost of the total system to supply approximately the entire world 1977 electricity demand of about 32 EJ to be about \$600 billion or an average of nearly \$40 billion/year with their assumption of a 15-year implementation period.

A major problem with their analysis is that they assumed a cost of \$44/kg for transportation into the needed orbit, assuming the existence of the planned "Heavy Lift Vehicle". A vehicle that can transport at such a cost has never materialized, in fact the current space transportation costs are at best around \$3000/kg

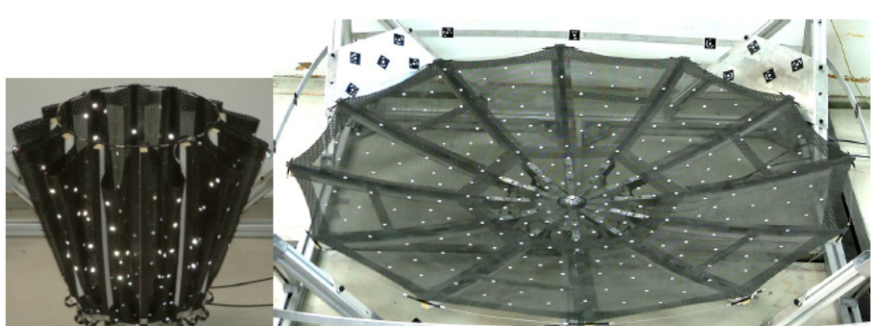

Fig. 12. A 1.6 m diameter precision reflector model with an umbrella-like deployment scheme, folded (left) and deployed (right).[58].

and more likely around $10,000/kg [60]. Conservatively assuming the latter cost and keeping all the NASA assumptions the same, the price of a 1 km diameter orbiting mirror would rise to $80.3 million, i.e., $102.30/m^2 (40.1 times higher) and would thus raise the price of generated electricity in similar proportion and make it highly uncompetitive. It is noteworthy that the cost of transportation to orbit is also the major obstacle for economic deployment and use of the SPS, and the only way to have competitive space power generation is to reduce the transportation costs to about $200/kg, i.e., by nearly 2 orders of magnitude, achievable by frequently planned but never commercially produced reusable launch vehicles (RLV) [10,11,14].

We have also conducted an economic feasibility analysis of the use of a space solar mirror system by approximating life time costs, profits and resulting revenues for three separate applications: (1) 24 h farm lighting, (2) night-time illumination in polar regions, and (3) greenhouse produce growing in polar regions.

The mirror aerial weight we determined was 11 g/m^2, which turned out to be close to the 10 gr/m^2 used in the NASA study [20], and considering all components of an aluminized 7.62 μm Kapton mirror reflector the cost was estimated at $2.05/m^2. Using the NASA data that show that reflector cost is about 48% of the total mirror cost without transportation, our estimate of the mirror area cost was thus $4.28/m^2.

For transportation costs, we used those for the Falcon 9 rocket in [61], at $7143/kg. i.e., $78.57/m^2 of mirror. Like in NASA's analysis we assumed a functional life of the mirror as 30 years and a discount rate of 15% but also calculated for a 5% discount rate to provide a range of values that come closer to present conditions. A lifetime maintenance cost of $1.27/m^2 (4.25 c/(m^{2}yr) was added. Summing the mirror and its launch costs, the total areal investment cost comes to $82.85/m^2 ($65.03 million per mirror) and the 4.25 c/(m^{2}yr) recurring maintenance costs.

From Eqs. (1) and (3) and as following NASA's estimates of the mirror area shown above and in Section 3 (as stated, considering that this mirror system will illuminate 5 ground sites around the world), each m^2 of the mirror illuminates 0.0923 m^2 of ground site area, at the planned insolation of 1.25 kW/m^2. This amounts to 115.4 W incident on the ground site per m^2 of the space mirror. The annual solar energy incidences are thus 39.4 GJ/m^2 ground area, or 3.64 GJ/m^2 of the space mirror.

If the energy is used for PV electricity generation at 15% conversion efficiency and normal incidence, this would steadily generate 187.5 W electricity per m^2 of the illuminated ground area, and thus 17.3 W electricity per m^2 of the space mirror, i.e., 151.6 kWh/yr (0.55 GJ/yr)/m^2 of the space mirror. At the typical US electricity price of $0.12/kWh, this should generate an annual revenue of $18.19/m^2 of the space mirror. The cost of the PV system is estimated to be $4/W$_{peak}$ [59,62], and considering the above result that the power generation is 17.3 W/m^2 of the space mirror, this would thus be $69.20/m^2 of the space mirror and is added to the $82.85/m^2 space mirror cost for a total areal investment cost of $152.05/m^2 of the space mirror.

The present value of the initial investment into the solar space mirror system for a discount rate of 5% is $278.98 and the net present value NPV = $278.98 − $152.05 = $126.93, and the internal rate of return (*IRR*) is 11.5%, indicating a financially rather viable investment. The *NPV*—based payback period is 11.2 years. If the discount rate was 15%, as assumed in the prior NASA study, then the *NPV* becomes negative, −$32.45, i.e., not financially viable. Discount rates up to 11.5% produce positive *NPV*.

Since transportation into orbit is in this analysis 52% of the needed capital investment, and since it is the cost item most likely to decrease significantly in the future, the same economic analysis was performed for the transportation costs of $200/kg, amounting to $2.20/m^2 and resulting in an overall mirror system cost of $6.48/m^2 and to total mirror + PV system cost of $75.68/(m^2 mirror). Now the investment achieves an *IRR* of 24.9% and becomes very viable even under the 15% discount rate, and we note that the mirror system, including its transport, becomes only 8.6% of the total system cost.

Using the solar radiation from the mirror to grow agricultural products in Polar Regions allows an extension of the growing season from the current 4 months [63] to 12 months per year. The benefit is obviously avoidance of the need for importation of expensive produce in the off seasons. Tomato growing has the most complete cost and quantity information and will be used for this scenario analysis. The average greenhouse grown tomato yield in arctic regions is 494 mt/ha of greenhouse land [64] (49.4 kg/m^2 land), i.e., 9.2 kg/m^2 of the space mirror. The price/lb of a domestic tomato is $1.50/lb, whereas an imported tomato in the very northern regions costs $6.00/lb [65]. The amount saved then by growing locally is US$4.50/lb or $45.52/m^2 of the space mirror. This creates annual revenues that are 2.5-fold higher than those estimated above for electricity generation. Furthermore, while not calculated here, the investment into a tomato growing greenhouse system may also be lower than the installation of a PV energy conversion system, with all of this pointing to the recommendation that such agricultural use is financially most viable.

Night time municipal illumination failed in this analysis to breakeven over the lifetime of the mirror, because of the relatively low density of needed streetlights, but it may be a rather viable application for both civilian and limitary purposes, when the demand justifies it.

Examining the three economic scenarios, both electricity generation and greenhouse growing in cold regions, and especially the latter, were shown to be profitable, and the profitability can increase significantly if and when the lower space transportation costs are reached.

It is noteworthy that the space mirror designs considered in the NASA analysis and also used here were not optimized. Furthermore, the costs of materials, of space deployment and of PV electricity generation are dropping. The economics can thus only improve, unless some unknown technical or environmental problem arises during the more detailed system development and testing.

The very high needed investments, of the order of more than $600 billion (about $40 billion per year for about 15 years), for space mirror system become more acceptable and appealing when compared with the expected accomplishment of providing renewable and relatively clean energy for satisfying energy of the order of the entire global demand, with relatively minimal global warming effects. These investments should also be compared with some other global financial values: in 2010 the annual world and OECD GDPs were about $63,000 billion [66] and $42,000 billion [67], respectively, the world defense budgets were $1437 billion (2.3% of GDP) [68]. The estimated annual expenditure for the space mirrors project are thus 0.06% of the World GDP, of the order of the World Bank subscribed capital of $44 billion for 2010.

Some other proposed high magnitude global renewable energy projects were estimated for the Space Power Satellite (SPS) [5,9] at $908 to $15,000/kWe, which for generating the current global power capacity of 4.4 TWe [2] would require an investment of $4000 to $65,000 billion, and for the DESERTEC project at close to $600 billion to supply by 2050 "only" 700 TWh/yr of electricity from the Saharan deserts [69]. The space mirror concept is predicted to incur much lower costs.

8. System sustainability

A huge and basically untested project like this one requires a very careful formal scientific sustainability analysis from the very

start [13]. Founded on the commonly used economic, environmental, and social pillars of sustainability, such an analysis in quantitative form is beyond the scope of this paper, but some major issues are identified and discussed, as follows.

8.1. The environmental pillar

- On the positive side:
  - the concept promises the satisfaction of a good part of the global energy demand from renewable energy,
  - alleviation by orders of magnitude of emissions and global warming, and
  - preservation of the remaining fossil fuels/hydrocarbons for other uses.
- Negative impacts are not minor and must be carefully considered and alleviated:
  - Emissions and noise from the launch vehicles; a current space launch typically produces 28 t of CO_2, and 23 t of toxic particulate matter [13].
  - Embodied emissions in the space mirror materials and construction
  - Effects on the atmosphere from the passage of the launch vehicles
  - Effects on the atmosphere from the added sunlight reflected to earth, including possible photochemical effects [70]; these may be accelerate global warming if greenhouse gas concentrations in the atmosphere continue rising, but may ultimately reduce global warming as fossil fuels are replaced by solar space mirror system.
  - The associated light glint (global) and scattering (near conversion sites) may add to the "ecological light pollution", a phenomenon well know among ecological and health hazards, is one that alters natural light regimes in terrestrial and aquatic ecosystems, and some of the catastrophic consequences of light for certain taxonomic groups are well known, such as the deaths of migratory birds around tall lighted structures, and those of hatchling sea turtles disoriented by lights on their natal beaches. The more subtle influences of artificial night lighting on the behavior and community ecology of species are still less well recognized and should be studied [71]. Light pollution also has detrimental effects on human lives possibly impairing vision [72] and altering the production of melatonin, the hormone that makes us sleep as it is released during darkness, and thus altering human circadian clock whose disruption has been linked to depression, insomnia, cardiovascular disease, and cancer. Also, according to the "First World Atlas of the Artificial Night Sky Brightness," two thirds of the US population and about half of the European Population can no longer see the Milky Way, thus destroying the aesthetic value of the night sky and impeding human connection to nature [73].
  - The additional light at night is an especially serious problem for astronomy since it prevents, or at the least makes very difficult to conduct astronomical observations and studies. At the same time, the associated launch capabilities developed for the space mirror system should advances possibilities for space astronomical laboratories [19]. A response to the strong criticisms about the effects of light that projects like "Novey Svet" (Section 1) may create was posted by the Russian Space Regatta [25]; they indicate that the problem must indeed be studied and any projects were and should be implemented with minimal damaging impact, but also list the large advantages that such lighting can provide.
  - Generation of a large amount of space debris, and risks of their impacts on other space vehicles and of fall to earth.

8.2. The economic pillar

As with any energy endeavor, the economics of the system metrics focused on the magnitude of the investment, and on the cost of the generated energy for use, all in comparison with alternatives methods for meeting the same objectives, are key. These were discussed in Section 7, and show some promise that the system can provide much of the global energy needs at a reasonable cost, especially if the cost of transportation to space is reduced to a few hundred \$/kg. This reduction is included in the planning by several national space organizations and private businesses and is synergistic with the need for low-cost space transport for other commercial applications.

To move towards sustainable development of the concept, the economic analysis must include monetization of all externalities, some of them negative and some positive, many of which are mentioned under the discussion of the environmental and social pillars in this section.

The magnitude of the needed capital investment, of above \$600 billion over about 15 years, should naturally be considered relative to other alternatives and to global economic conditions.

In such a novel and large project the risks play a key role. Gradual, incremental, introduction of the system, with careful preparation and monitoring would be necessary.

8.3. The social pillar

- Some human impacts
  - Those related to health and aesthetics are described under the above-discussion of the Environmental Pillar;
  - Public anxiety due to large number of satellites in orbit; self destruction of failing mirrors to safe levels would be a way to alleviate this problem somewhat;
  - It is very likely that the project would make significantly positive contributions to employment, education, and creativity with associated beneficial spinoffs;
  - Generation of adequate energy to about 1/6 of the world population which lacks it will certainly improve their health and education and improve chances for reducing poverty.
- International space stewardship: There is considerable and very justified concern about assuring internationally fair and safe use of space. This certainly would apply to the massive proposed space mirrors project, which in the case of NASA's SOLARES proposes to place 80,000 1-km diameter mirrors in the sky, with all the associated impacts. The Outer Space Treaty ratified by the UN in 1967 [74] provides the basic framework on international space law, including the following principles:
  - "the exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all mankind;
  - outer space shall be free for exploration and use by all States;
  - outer space is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means;
  - States shall not place nuclear weapons or other weapons of mass destruction in orbit or on celestial bodies or station them in outer space in any other manner;
  - the Moon and other celestial bodies shall be used exclusively for peaceful purposes;
  - astronauts shall be regarded as the envoys of mankind;
  - States shall be responsible for national space activities whether carried out by governmental or non-governmental entities;

- States shall be liable for damage caused by their space objects; and
- States shall avoid harmful contamination of space and celestial bodies."

As of October 2011, 100 countries and states are parties to the treaty, while another 26 have signed the treaty but have not completed ratification. The treaty remains, however, very incomplete and lacks some essential detail and clearly effective enforcement measures. Amongst the obvious omissions are industrial exploration of minerals from asteroids, intellectual property of space research, and space pollution [75–77].

A much more solid treaty must be developed to ensure internationally fair and safe deployment and use of the space mirrors project.

9. Conclusions and recommendation

A critical review of the current status of the space mirrors concept was conducted, thin film aluminized Kapton mirrors were manufactured and optically and mechanically tested to examine their property changes when exposed to a cryogenic temperature, an economic analysis related to several applications was performed, and leading issues that must be taken into account in the sustainability analysis of the concept were described. We add, without analysis, the possibility of using the space mirrors for shading the earth, a possible application that may be locally useful for a number of obvious reasons, or as a geo-engineering way to reduce global warming. In that extreme case, the mirrors, or some of them, could be turned towards the sun and thus prevent the solar radiation from reaching the atmosphere and earth area that is thereby placed in the mirrors' shadow.

Our experiments with thin film mirror have shown that the reflectance at 77 K is always higher than that at 300 K, about 1.42 fold on average in the peak solar wavelength range of 470–700 nm. The imperfection surface density is lower for the cryogenic temperature. The ultimate tensile strength and tensile modulus increased at the cryogenic temperature, consistent with the behavior of polymers like Kapton.

As in any large energy development endeavour, it is impossible to eliminate all negative impacts, but just to render them tolerable and sustainable, especially relative to other available options. The overall concept sustainability, especially taking into account the environmental and social impacts and their associated costs, must be analyzed carefully and quantitatively, and all externalities must be included in its future evaluations.

Without consideration of these externalities, our economic analysis agrees with NASA's and Ehricke's, published in the late 1970s [18–23], that if transportation costs to mirror orbit are reduced to a few hundred \$/kg, as planned, the use of orbiting space mirrors for providing energy to earth is an investment with a good rate of return and a cost effective alternative to satellite solar power stations (SPS) and to terrestrial renewable and conventional power sources.

This energy concept is very appealing relative to other options for addressing the severe energy and global warming problems that we face, and deserves much and urgent R&D attention.

Acknowledgments

My former students Kamal Shair, Betsy Rosenblatt, and Travis Schlegel have conducted the experiments presented in Section 6.2 and contributed to other parts of this paper; I am especially grateful to Kamal Shair who continued his cooperation about their work. I am grateful to William P. Gilbreath and Stuart W. Bowen, authors of some the seminal NASA papers on space mirrors, for their answers to my questions. Iris Chu and Eri Mizukane have been very helpful in the literature search for this study.

References

[1] Lior N. The ECOS 2009 World Energy Panel: an introduction to the panel and to the present (2009) situation in sustainable energy development. Energy 2011;36:3620–8.
[2] Lior, N Sustainable energy development: a brief introduction to the present (May 2011) situation, accepted for publication in Energy, 2012.
[3] Glaser PE. Power from the sun: its future. Science 1968;162:857–61.
[4] Glaser PE, Davidson FP, Csigi KI, editors. New York: Ellis Horwood; 1993.
[5] Mankins JC. Space solar power: a major new energy option? Journal of Aerospace Engineering 2001;14(2):38–45.
[6] Mankins, JC (USA), Kaya, N. (Japan), editors. Space solar power: the first international assessment of space solar power: opportunities, issues and potential pathways forward. August 2011, International Academy of Astronautics, 6 rue Galilée, BP 1268-16, 75766 Paris Cedex 16, France, ISBN/EAN 978-2-917761-11-3.
[7] Criswell DR, Thompson RG. Data envelopment analysis of space and terrestrially-based large scale commercial power systems for earth: a prototype analysis of their relative economic advantages. Solar Energy 1996;56: 119–31.
[8] Brown WC. The history of wireless power transmission. Solar Energy 1996;56:4–21.
[9] Woodcock GR. Solar satellites—space key to our power future. Astronautics and Aeronautics 1977;15:30–43.
[10] NASA, solar power satellite concept evaluation. vol. 1, NASA JSC-12973, July 1977.
[11] Lior N. Power from space. Energy Conversion & Management Journal 2001;42(15-17):1769–805.
[12] Tarlecki Jason, Lior Noam, Zhang Na. Analysis of thermal cycles and working fluids for power generation in space. Energy Conversion & Management 2007;48:2864–78.
[13] Zidanšek A, Ambrožić M, Milfelner M, Blinc R, Lior N. Solar orbital power: sustainability analysis. Energy 2011;36:1986–95.
[14] National space society, 〈http://www.nss.org/settlement/ssp/index.htm〉, [accessed 2/19/2012].
[15] Krafftehricke.com Krafft A. Ehricke and America in Space. [〈http://www.krafftaehricke.com/ehricke_power_relay_satellite_2.php〉], [accessed 2/19/2012].
[16] Oberth H. Wege zur Raumschiffahrt. Berlin: Oldenburg Verlag; 1929 (Translation, NASA TT-F-662).
[17] Buckingham AG, Watson HM. Basic concepts of orbiting reflectors. Journal of Spacecraft 1968;5:852–3.
[18] Billman, KW, Gilbreath, WP, Bowen, SW Introductory assessment of orbiting reflectors for terrestrial power generation. NASA TM X-73,230, 1977.
[19] Billman, KW, Gilbreath, WP, Bowen, SW Satellite mirror systems for providing terrestrial power: system concept. paper AAS-77-240, 23rd meeting of the AAS, San Francisco, Calif., Oct. 1977.
[20] Billman, KW, Gilbreath, WP, Bowen, SW SOLARES-a new hope for solar energy? Alternative energy sources, In: Proceedings of the Miami international conference, Miami Beach, Fla., December 5–7, 1977. volume 1. (A79-33984 13-44) Washington, D.C., Hemisphere Publishing Corp., 1978, p. 233-255. IISSN: 0278-1662.
[21] Gilbreath, WP, Billman, KW Bowen, SW Enhanced solar energy options using earth-orbiting mirrors, In: Proc. 13th intersociety energy conversion engineering conf. San Diego, California August 20–25, 1978, Paper 789186, vol. 2, 1528–1534 published by the society of automotive engineers, Inc. 400 Commonwealth Drive, Warrendale, PA 15096.
[22] Ehricke Krafft A. Kraftsoletta – eine Industrie-Sonne fur Europa – Moglichkeiten kostenrealistischer solarenergie. Astronautik 1977;3:85–7.
[23] Ehricke Krafft A. Space light: space industrial enhancement of the solar option. Acta Astronautica 1979;6 pp. 1515_1633.
[24] Sistach, LA The moon orbital mirror. The international academy of astronautics, and the international institute of space law, In: 54th international astronautical congress of the international astronautical federation, 29 Sept. 2003, Bremen, Germany.
[25] Space Regatta Consortium. An open letter to astronomers professional and amateur. 〈http://src.space.ru/page_30e.htm〉, [accessed 2/19/2012].
[26] Ashurly MZ. Space-based mirror reflector of solar radiation. Journal of Optical Technology 2000;67(6):577–9.
[27] SP Korolev Rocket and space corporation "energia". 〈http://www.energia.ru/english/〉, [accessed 2/19/2012].
[28] Shpakovsky N. Space mirror. space mirror. The TRIZ Journal 2012 accessed 2/19/〈http://www.triz-journal.com/archives/2002/06/e/index.htm〉.

[29] Garner, C, Diedrich, D, Leipold, M A summary of solar sail technology developments and proposed demonstration missions, jet propulsion laboratory report JPC · 99 · 2697.
[30] Freiman, Chana Mirror, mirror, up in space?—fpace mirror for rroviding light. CBS Interactive, 3 Dec. 1993. Web. 10 Dec. 2011. 〈http://findarticles.com/p/articles/mi_m1590/is_n7_v50/ai_14719235/〉, [accessed 2/19/2012].
[31] Leary, Warren E. Russians to test space mirror as giant night light for earth—New York Times. The New York Times—Breaking News, World News & Multimedia. The New York Times, 12 Jan. 1993. Web. 11 Dec. 2011. 〈http://www.nytimes.com/1993/01/12/science/russians-to-test-space-mirror-as-giant-night-light-for-earth.html?pagewanted=all〉, [accessed 2/19/2012].
[32] Whitehouse, David BBC News |Sci/Tech| turning night into day. BBC News—home. 4 Feb. 1999. Web. 11 Dec. 2011. 〈http://news.bbc.co.uk/2/hi/science/nature/271224.stm〉, [accessed 2/19/2012].
[33] Hamilton, Jon Is a brighter earth a better one?: NPR. NPR: National Public Radio: News & Analysis, World, US, Music & Arts: NPR. Npr, 21 Dec. 2006. Web. 11 Dec. 2011. 〈http://www.npr.org/templates/story/story.php?storyId=6655690〉, [accessed 2/19/2012].
[34] Folger, Tim New moon – Russian satellite acts as a mirror to light remote areas – 1993 – the year in science. Discover Jan. 1994. BNet. 〈http://findarticles.com/p/articles/mi_m1511/is_n1_v15/ai_14898893〉, [accessed 2/19/2012].
[35] Pignolet, G (1996). Solar Sails. The flight of Znamia. Retrieved December 10, 2007, from 〈http://www3.ec-lille.fr/~u3p/textang/izamiaa.html〉, [accessed 2/19/2012].
[36] Steen, M (1999, August 2). UK astronomers attack Russian space mirror plan. 〈http://www.planetark.com/avantgo/dailynewsstory.cfm?newsid=1073〉, [accessed 2/19/2012].
[37] Wong, Wayne SBIR inflatable concentrator tested for space. Aerospace technology innovation. Sept.–Oct. 2001. NASA. 〈http://nctn.hq.nasa.gov/innovation/innovation95/6-smallbiz3.html〉, [accessed 2/19/2011].
[38] Fink D, Biersack JP, Städele M. On the performance and lifetime of solar mirror foils in space. Space Solar Power Review 1985;5:91–100.
[39] Kutz Myer. Handbook of environmental degradation of materials. William Andrew Publishing; 2005 pp. 479–487.
[40] Friedman, L Carroll, W, Goldstein, R, Jacobson, R, Kievit, J, Landel, R, Layman, W, Marsh, E, Ploszaj, R, Rowe, W, Ruff, W, Stevens, J, Stimpson, L, Trubert, M, Varsi, G, Wright, J, MacNeal, R, Solar sailing, the concept made realistic. Paper 78–82, AIAA 16th aerospace sciences meeting, Huntsville, Ala., Jan. 1978.
[41] Brogren M, Helgesson A, Karlsson B, Nilsson J, Roos A. Optical properties, durability, and system aspects. Solar Energy Materials & Solar Cells 2004;82:387–412.
[42] Barron L W, Neidrich J, Kurinec SK. Optical, electrical, and structural properties of sputtered aluminum alloy thin. Thin Solid Films 2007;512:3363–72.
[43] Adams RO, Nordin CW, Fraikor FJ, Masterson KD. Co-sputtering of aluminum-silver alloy mirrors for use. Thin Solid Films 1979;63:151–4.
[44] Yang M, Zhou C, Jiang D. Comparison of different strategies to realize highly reflective thin film coatings. Infrared Physics & Technology 2008;51:572–5.
[45] Gulino, DA The survivability of large space-borne reflectors under atomic oxygen and micrometeoroid impact. NASA technical memorandum 88914, prepared for the 25th aerospace sciences meeting sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 12–15, 1987.
[46] Callister WD, Rethwisch DG. Fundamentals of materials science and engineering: an integrated approach. New York: Wiley; 2007 763-64.
[47] Griffin, Michael D; French, JR Space Vehicle Design (2nd ed.), (pp. 80 and Table 3.5 on pp. 87). American Institute of Aeronautics and Astronautics. 〈http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=1597&VerticalID=0〉, [accessed 2/19/2012].
[48] ibid, p. 431, [accessed 2/19/2012].
[49] Finckenor, MM, Dooling, D Multilayer insualtion material guidelines. (1999): 20–21. NASA technical reports server. 〈http://ntrs.nasa.gov/search.jsp?R=1003560&id=1&qs=Ntt%3Dmultilayer%252Binsulation%252Bguidelines%26Ntk%3Dall%26Ntx%3Dmode%2520matchall%26N%3D0%26Ns%3DHarvestDate%257c1〉, [accessed 2/19/2012].
[50] Bunshah, RF (1994). Handbook of deposition technologies for films and coatings—science, technology and applications (2nd ed.), (pp. 237–239). William Andrew Publishing/Noyes.
[51] Barron LW, Neidrich J, Kurinec SK. Optical, electrical, and structural properties of sputtered aluminum alloy thin. Thin Solid Films 2007;512:3363–72.
[52] 3 M company, reflective film; the best we could tell from communications with 3 M, the vendor Acro Solar Lasers Company (〈http://www.acrosolarlasers.com/mirror.html〉), and the literature, is model 3 M ECP-305+, consisting of 0.1 mm UV-stabilized polymethylmethacrylate (PMMA) film with an evaporated reflective Ag layer, a protective Cu layer, and a pressure-sensitive adhesive layer on its back for application to a surface. Discontinued by 3 M. Sold at the time of our study by Acro Solar Lasers Company as "Laser Silver Mirror Film", rated by them as 94% reflective.
[53] Callister WD, Rethwisch DG. Fundamentals of materials science and engineering an integrated approach. New York: Wiley; 2007 pp. 816-7.
[54] DuPont. Summary of properties for Kapton polyimide films. Dupont electronics: Kapton polyimide film. 2008. Dupont. 15 Feb. 2009 〈http://www2.dupont.com/Kapton/en_US/assets/downloads/pdf/summaryofprop.pdf〉, (pp. 3).
[55] Lichodziejewski, D, Derbès, B, West, J, Reinert, R, Belvin, K, Pappa, R Bringing an effective solar sail design toward TRL 6. Paper AIAA 2003-4659, 39th AIAA joint propulsion conference, 2003.
[56] Brown, MA Mechanical design of a kilometer-sized solar sail AIAA 2010-2586 12, 15 April 2010, Orlando, Florida, pp. 1010–1023.
[57] Datashvili, L, Baier, H Building blocks of large deployable precision membrane reflectors, In: Proceedings of the 42nd AIAA/ASME structures, structural dynamics and materials conference, AIAA paper no. 2001-1478, April 2001, Seattle.
[58] Datashvili, L, Baier, H Wehrle, E, Kuhn, T, Hoffmann, J Large shell-membrane space reflectors, In: 51st AIAAIASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference, 18th AIAA 2010-2504 12, 15 April 2010, Orlando, Florida, 〈http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCMQFjAA&url=http%3A%2F%2Ftrs-new.jpl.nasa.gov%2Fdspace%2Fbitstream%2F2014%2F17657%2F1%2F99-1091.pdf&ei=jTIxT8eZObGL0QG1y_3sBw&usg=AFQjCNE1HKFVSjWtG6OovR3rHSPlCTWCJQ〉, [accessed 2/19/2012].
[59] Solarbuzz, module prices – retail price summary – February 2012 Update. 〈http://solarbuzz.com/facts-and-figures/retail-price-environment/module-prices〉, [accessed 2/19/2012].
[60] Koelle, DE Cost efficiency as design and selection criterion for future launch vehicles acta astronautica volume 57, issues 2–8, July–October 2005, Pages 623–629.
[61] Spacex space exploration technologies. Falcon 9 overview. March 2009. 〈http://www.spacex.com/falcon9.php〉, [accessed 2/19/2012].
[62] REN 21 (Renewable Energy Policy Network for the 21st Century). Renewables global status report 2011 update, 〈http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCQQFjAA&url=http%3A%2F%2Fwww.ren21.net%2Fgsr&ei=O6NBT9-OM8Le0QGQtdDABw&usg=AFQjCNGLdExkI5-dh3xR7mIFxYL0hMIqQA〉, [accessed 2/19/2011].
[63] Nield, Jeff Growing food in the arctic circle. August 29, 2008. 〈http://www.treehugger.com/files/2008/08/growing-food-in-the-arctic-circle.php〉, [accessed 2/19/2012].
[64] Cook, Roberta, Calvin, Linda. North American greenhouse tomatoes emerge as a major market force. Amber waves, April 2005, 〈http://www.ers.usda.gov/Amberwaves/April05/Features/GreenhouseTomatoes.htm〉, [accessed 2/19/2012].
[65] Google News. Greenhouses a growing trend in the arctic. Google News. August 18, 2007. 〈http://afp.google.com/article/ALeqM5jtwCQYmXOIt0ajYvTNnL4Jrwkyqg〉, [accessed 2/19/2012].
[66] World Bank. World GDP. 〈http://data.worldbank.org/indicator/NY.GDP.MKTP.CD/countries/1W?display=graph〉, [accessed 2/19/2011].
[67] OECD. Gross domestic product in US dollars. OECD 2012 〈http://www.oecd-ilibrary.org/sites/gdp-cusd-table-2012-1-en/index.html;jsessionid=cld88aof9i8.delta?contentType=&itemId=/content/table/gdp-cusd-table-2012-1-en&containerItemId=/content/table/gdp-cusd-table-2012-1-en&accessItemIds=&mimeType=text/html〉, [accessed 2/19/2012].
[68] Stockholm International Peace Research Institute (SIPRI). 〈http://milexdata.sipri.org/〉, [accessed 2/19/2012].
[69] DESERTEC foundation, clean power from deserts. 〈http://www.desertec.org/〉, [accessed 2/19/2012].
[70] Ching BK. Space power systems – what – environmental impact? Astronautics & Aeronautics 1977;15:60–5.
[71] Longcore T, Rich C. Ecological light pollution. Frontiers in Ecology and the Environment 2004;2(No. 4):191–8.
[72] Laframboise JG, Chou BR. Space mirror experiments: a potential threat to human eyes. Journal of the Royal Astronomical Society of Canada 2000;94(237-240).
[73] Chepesiuk R. Missing the dark: health effects of light pollution. Environ Health Perspect 2009;117:A20–7.
[74] U.N. The outer space treaty, 〈http://www.oosa.unvienna.org/oosa/SpaceLaw/outerspt.html〉, [accessed 2/19/2012].
[75] European Centre for Space Law (ECSL). Space policy documents and useful readings on regional and national space legislations. 〈http://www.esa.int/SPECIALS/ECSL/SEMDTNLTRJG_0.html〉, [accessed 2/19/2012].
[76] Oosterlinck, Rene Who owns and regulates space and why are space laws necessary?. European Space Agency (ESA) 〈http://www.youtube.com/watch?v=ADTg5CfNNUA〉, [accessed 2/19/2012].
[77] NASA. History: Glenn contributions to deep space 1. May 21, 2008 update, NASA. 〈http://www.nasa.gov/centers/glenn/about/history/ds1.html〉, [accessed 2/19/2012].